Tropospheric wind measurements obtained with the Goddard Lidar Observatory for Winds (GLOW): Validation and Performance

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ABSTRACT

The Goddard Lidar Observatory for Winds (GLOW) is a mobile Doppler lidar system which uses direct detection Doppler lidar techniques to measure wind profiles from the surface into the lower stratosphere. GLOW is intended to be used as a field deployable system for studying atmospheric dynamics and transport and can also serve as a testbed to evaluate candidate technologies developed for use in future spaceborne systems. In September of 2000 GLOW particpated in a three week intercomparison experiment at the GroundWinds facility in North Glen, NH. More than 50 hours of line-of-sight wind profile data were obtained in a wide variety of conditions including both day and night operation. Typical clear air lidar wind profiles extended to altitudes of 20 km with a 1 km vertical resolution and 1 minute averaging. A description of the mobile system is presented along with the examples of lidar wind profiles obtained with the Goddard system during the New Hampshire experiment.

1. Introduction

The Goddard Lidar Observatory for Winds (GLOW) is a mobile wind lidar system utilizing direct detection Doppler lidar techniques for measuring the wind (Figure 1). The GLOW mobile lidar system has a twofold purpose:

1) to provide wind profile measurements from the surface into the stratosphere for use in scientific measurement programs and
2) as a testbed for validating the performance of new technologies and measurement techniques proposed for use in future spaceborne applications.

Figure 1 - The mobile Doppler lidar system is mounted in a modified delivery van. The 45 cm clear aperture azimuth-over- elevation scanner is mounted on the roof to allow full sky access.

The Doppler lidar receiver used in the GLOW lidar system is based on the edge technique for lidar wind measurements[1] .The edge technique can use either aerosol or molecular backscatter for the Doppler wind measurement. The basic principles of the edge technique have been verified in lab[2] and atmospheric lidar wind experiments[3, 4]. The edge technique is an example of a class of direct detection Doppler methods that are related by the common technologies employed in the measurement. These technologies include the single frequency solid-state laser, high resolution optical filters, high efficiency low noise detectors capable of photon counting and large aperture, non-diffraction limited telescopes. A variety of direct detection Doppler wind lidar measurements have recently been reported [5, 6, 7, 8].

NASA Goddard has been actively involved in the development of direct detection Doppler lidar methods and technologies to

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meet the broad range of wind observing needs of the atmospheric science community. Applications include spaceborne observation of global winds[9] and ground and airborne measurements of winds for investigation of mesoscale dynamics and atmospheric processes.

To extend the operation of the edge technique into the troposphere and lower stratosphere we have developed a variation of the edge technique called the double edge technique. The double edge method utilizes two high spectral resolution optical filters located symmetrically about the outgoing laser frequency. The details of the double edge method have been recently reported for lidar systems measuring the Doppler shift from either aerosol[10] or molecular[11] backscattered signals. Atmospheric measurements of winds have been reported using both the aerosol[12] and molecular[4] implementations of the double edge technique.

In this paper we describe a ground based Doppler lidar system that has been integrated into a modified van to allow field deployment and operations. The system includes an aerosol double edge receiver optimized for aerosol backscatter Doppler measurements at 1064 nm and a molecular double edge receiver designed to operate at 355 nm. The lidar system is described concentrating on the uv molecular Doppler implementation. The performance of the system is illustrated using lidar radial wind profiles obtained in North Glen, NH as part of the GroundWinds validation and intercomparison experiment held in September, 2000.

2. Lidar System Description

The GLOW lidar system is integrated in the back of a modified delivery van. The laser, a 45 cm aperture telescope and beam pointing optics are mounted on an optical bench that is bolted to the truck frame. A 45 cm aperture scanner is mounted on the roof to allow access to the atmosphere. The scanner provides full hemispherical pointing using motor driven azimuth and elevation mirrors. The matching 45 cm, f/2.5 Dall Kirkham telescope is mounted below the scanner to collect the backscattered signal. The collected light is coupled directly to a fiber optic cable. The fiber delivers the signal to the Doppler receivers and also serves as the field stop for the system.

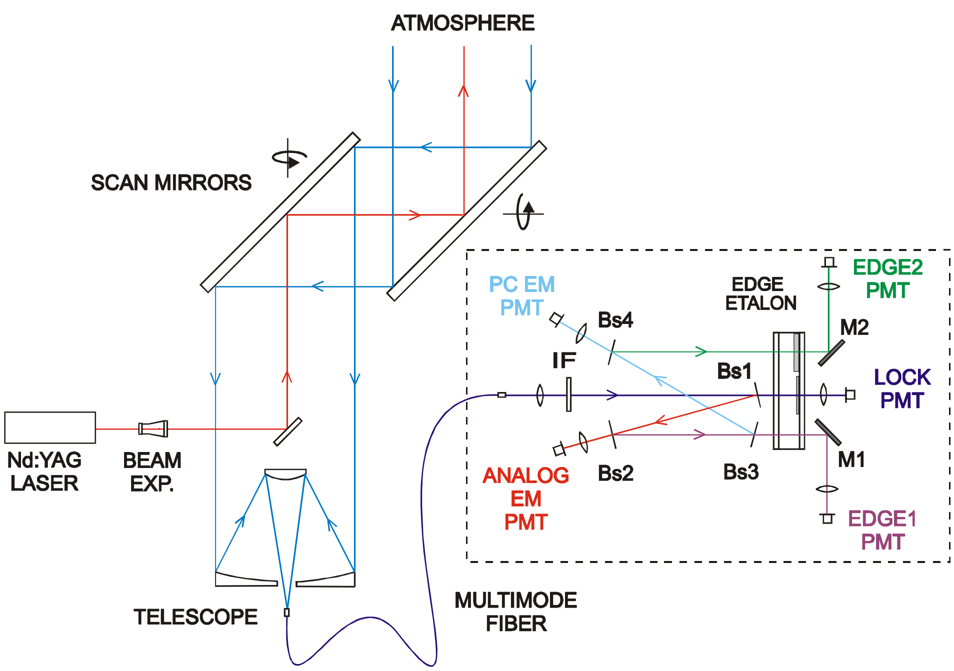

Figure 2 - Optical layout of the GLOW lidar system. The molecular receiver is shown in the dashed box.

The design of the lidar system is modular to allow incorporation of new technologies (lasers, scanning optics, telescopes, receivers) as they become available. The optical layout of the system is shown in Figure 2. The laser is an injection seeded, flashlamp pumped Nd:YAG laser which has a repetition rate of 10 Hz. The pulse length is 15 ns and the spectral width is 40 MHz at the fundamental wavelength of 1064 nm. The laser also includes second and third harmonic generation optics to produce 532 nm or 355 nm pulses. We normally operate the laser with an energy of 120 mJ/pulse at 1064 nm for the aerosol measurements. An optical amplifier is added to the laser for the molecular measurements at 355 nm and after tripling we typically operate with 70 mJ/pulse of uv energy.

We currently have two receivers in the van, one for aerosol backscatter wind measurements and one optimized for molecular backscatter. The two receivers are mounted on separate baseplates and are coupled to the telescope via a multimode fiber optic cable. The optical interface is the same for both receivers and the choice of which receiver to use is made by simply coupling the appropriate fiber to a connector mounted in the telescope focal plane. The molecular receiver is new and we have concentrated on integration and demonstration of this newer capability during the initial months of operation of the mobile Doppler lidar system. The following sections will briefly describe the new molecular receiver and present the initial wind measurements made with the molecular double edge lidar.

3. Molecular Double Edge Receiver

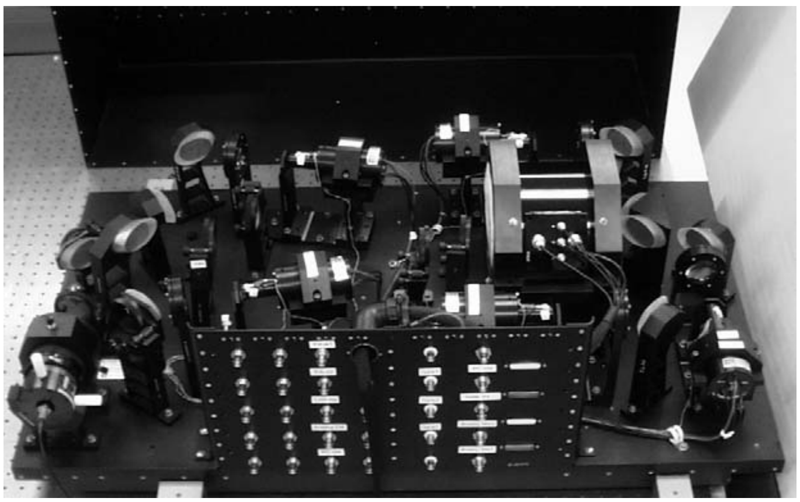

Figure 3 - Double edge molecular receiver with cover removed. The incoming fiber optic cable is connected to the collimator in the lower left corner. The tunable etalon is the large cylinder to the right.

The molecular double edge receiver was built as an engineering prototype of the system designed for Zephyr, a direct detection Doppler lidar demonstration mission proposed for flight on the Shuttle as part of NASA's New Millennium Program[13] (Gentry et al 1998b). The design follows the general principles described recently by Flesia and Korb 1999. It is also similar in concept to the Rayleigh Doppler lidar system described and successfully operated at OHP in France [5,8].

A picture of the receiver with the cover off is shown in Figure 3. The fiber optic from the telescope is coupled to the collimator (lower left) to produce a collimated beam of 35 mm diameter. This beam is split by beamsplitters into a total of five channels, three of these are directed along parallel paths through a Fabry-Perot etalon filter. Two of these etalon channels (the 'edge' channels) have PMTs operating in photon counting mode. The third etalon channel is used as a reference and uses a PMT operated in current or analog mode. The other two channels serve as energy monitor channels, one has a photon counting PMT and the other has an analog mode PMT. The energy monitor channels provide intensity normalization of the respective etalon channels during calibration.

A capacitively stabilized piezo-electrically tunable Fabry-Perot etalon is used for the high spectral resolution edge filter. The etalon has three sub-apertures each with a diameter of 38 mm. The spectral bandpasses of two of the sub-apertures have been offset from one another and with respect to the third. The magnitude of the offset is defined by a small 'step' coating which has been deposited in two of the apertures on one of the etalon plates prior to deposition of the reflective coating. This produces the double edge configuration described in Flesia and Korb 1999 along with a third intermediate channel which is used in sampling the outgoing laser frequency as a reference.

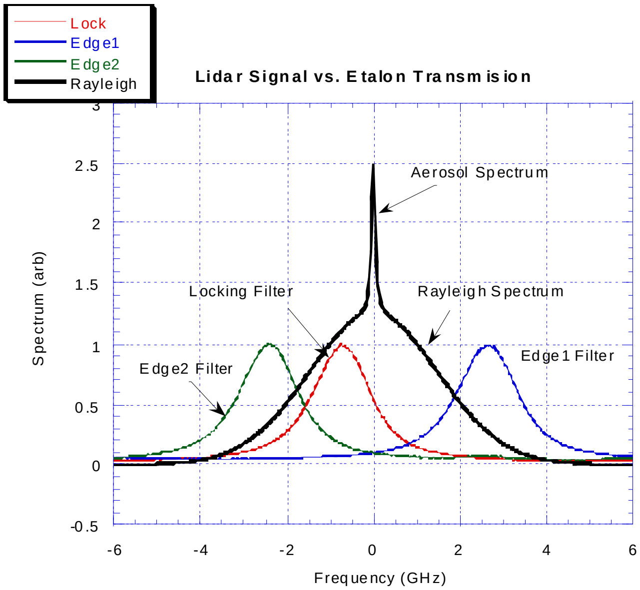

Figure 4 - A spectral scan of the three etalon bandpasses (Edge 1, Edge2 and Locking filter) are shown along with a model spectrum of the atmospheric backscattered signal.

A calibration scan of the etalon transmission is shown in Figure 4. A calibration scan such as this provides precise knowledge of the etalon transmission and spectral separation of the 'edge' channels required to determine the winds from the lidar data.

To produce this calibration scan the three etalon bandpasses are scanned simultaneously by stepping the piezoelectric elements through approximately one free spectral range (12 GHz). A simulation of the backscattered signal spectrum is also shown for reference. The characteristic spectral signature of the narrow aerosol 'spike' is shown superimposed on the thermally broadened molecular backscattered specturm. The two edge filter channels (labeled 'Edge 1' and 'Edge2') are located in the wings of the molecular broadened spectrum at a position which has equal sensitivity to Doppler shifts for either molecular or aerosol backscattered signal. This makes the wind measurement insensitive to the aerosol/molecular backscatter ratio. The reference channel ('Locking Filter') is located such that the outgoing laser frequency appears on the edge of the 'Locking' fringe. A measurement of the outgoing laser frequency is made as a reference to remove short term frequency jitter and drift and also can be used to actively 'lock' the etalon to the laser frequency in a servo loop in order to maintain the symmetric arrangement of the filters about the outgoing laser frequency.

The photon counting PMTs provide high detection sensitivity in the upper troposphere and stratosphere where the return signals are small. The analog PMT signals are sampled with a boxcar integrator and the data are stored for every 10 shots. The photon counting signals are binned in a multichannel scalar and integrated for a selectable number of shots prior to storage. Typical integration times are 30 seconds (300 shots) to 100 seconds (1000 shots). An example of the signals from the three photon counting channels are shown in Figure 5. The integration time for these signals is 30 seconds (300 shots) and the data are binned with a range resolution of 250 m. These data were obtained during the afternoon of September 25, 2000 as part of the GroundsWinds validation experiment to be described in the following section. The laser pulse energy for these measurements was 70 mJ. A narrowband interference filter is included in the receiver to restrict the broadband solar background during daytime operation. The 25 mm aperture of this filter is smaller than the receiver design beam diameter of 35 mm. This limited the effective telescope collecting aperture to about 30 cm. The PMT's have been gated off below approximately 5 km altitude to avoid saturation.

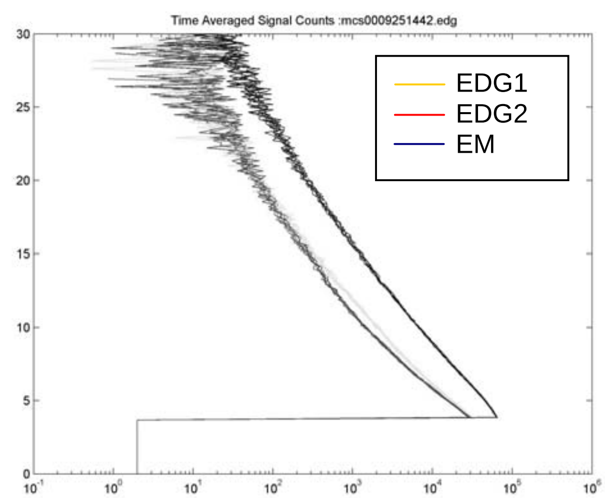

Figure 5 – Photocounts detected in the molecular receiver for the two edge channels, EDG1 and EDG2 and the energy monitor, EM. The range resolution is 250m and 300 shots are averaged.

As noted above, the choice of etalon filter bandpass and separation of the channels the wind velocity can be uniquely determined by measuring the ratio of these two edge signals. In Figure 5 the magnitude of the two edge channel signals is approximately equal at 5 km and above 20 km. However, there is a significant difference in the two edge signals apparent between 7 and 18 km peaking at around 11 km. This difference in observed signal is a manifestation of the Doppler shift due to the wind as observed through the double edge filters. This will be apparent in the discussion to follow (see figure 6).

4. Lidar Observations

The GLOW Doppler lidar began atmospheric testing using the molecular receiver in October, 1999. Following an initial period of testing and calibration we began making wind measurements in early November, 1999. A validation experiment was held at Goddard that compared the lidar derived wind speed and direction with data obtained from launches of multiple rawinsondes[4]. While these experiments demonstrated the basic abilities of the lidar to profile winds the mobility of the system remained to be demonstrated. The first opportunity to test the system in a field deployment was in September 2000 when the GLOW system participated in the GroundWinds validation campaign held from September 18-29, 2000 at the site of the GroundWinds lidar observatory in North Glen, NH. The experiment included three Doppler lidars, a MiniMOPA coherent Doppler lidar operated by NOAA Environmental Technology Laboratory and the University of New Hampshire's GroundWinds lidar, another direct detection Doppler lidar built by Michigan Aerospace Corporation for UNH. In addition to the three lidar systems, the experiment included a profiler and rawinsondes launched from the site for intercomparison. A primary objective of the campaign was to operate the lidars in a coordinated fashion with each lidar pointing at common azimuth and elevation angles to produce radial wind profiles which could be intercompared. Each lidar system had somewhat different base spatial and temporal sampling intervals so it was agreed to process all lidar profiles to a common spatial and temporal grid to facilitate the intercomparison of the radial wind profiles. The time interval for averaging was 60 seconds and the vertical sampling was 0.25 km for altitudes below 3 km and 1 km for altitudes from 3 to 20 km. Raw GLOW signal data as shown in Figure 5 were processed accordingly to produce sets of consecutive one minute radial wind profiles.

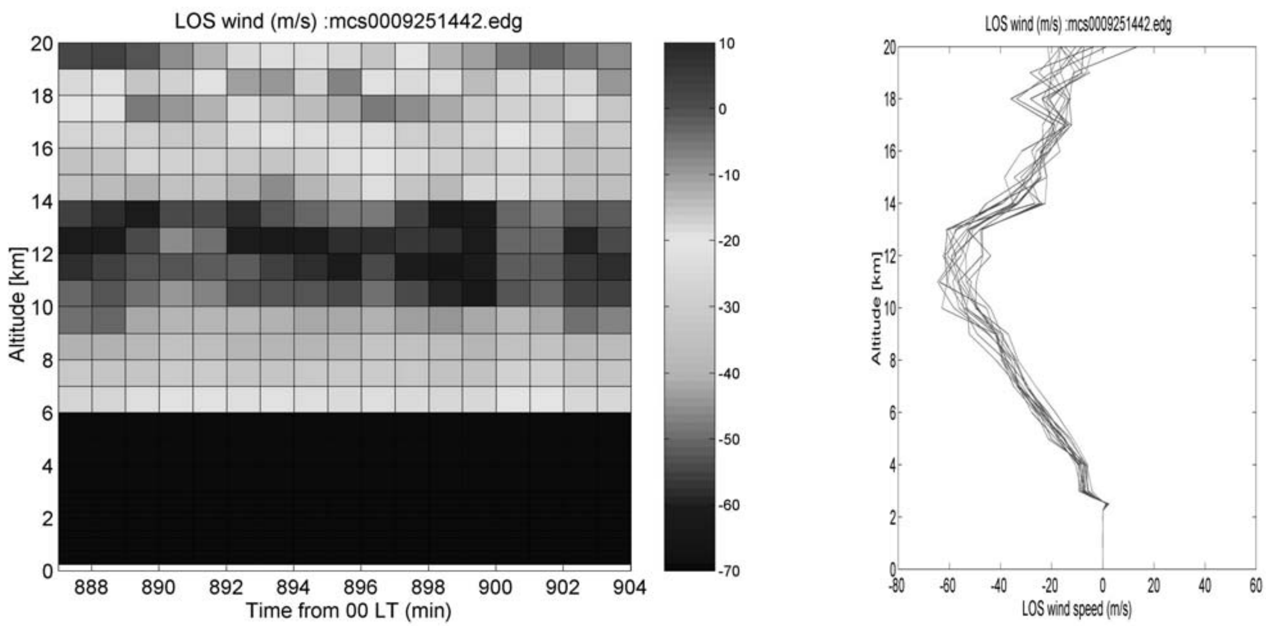

Figure 6 - a) A color plot of one minute radial wind profiles obtained with the GLOW lidar system on the afternoon of September 25, 2000. b) Same profiles overlaid in a plot of altitude vs velocity.

Figure 6a shows the radial wind velocity field measured by GLOW during a 17 minute period on the afternoon of September 25, 2000. The local time is around 14:45 EDT and the lidars were pointed at a 45 deg elevation and an azimuth of 80 degrees Wind velocity is shown as a function of altitude (y-axis) and time (x-axis) with the time scale given in elapsed minutes from 00 EDT. The radial wind velocity in m/s for each altitude interval is mapped to the color scale given on the right. An alternate 2-D representation of the 17 lidar profiles is shown in Figure 6b. A strong jet with a peak radial velocity of around 58 m/s (82m/s horizontal wind speed) is clearly observed at 11 km. There is substantial variability in the observed velocity with time. This is due to both the random error associated with the instrument and atmospheric variability during the sampling time. A first order estimate of this total variability is shown in Figure 7 which is a plot of the mean and standard deviation of the 17 profiles from Figure 6. Also shown are two wind profiles determined from rawinsondes launched within an a few hours of the lidar measurement time. In this case the rawinsonde measured wind is projected to the lidar line-of sight. Good agreement is shown up to around 11 km, the maximum altitude available for these sondes.

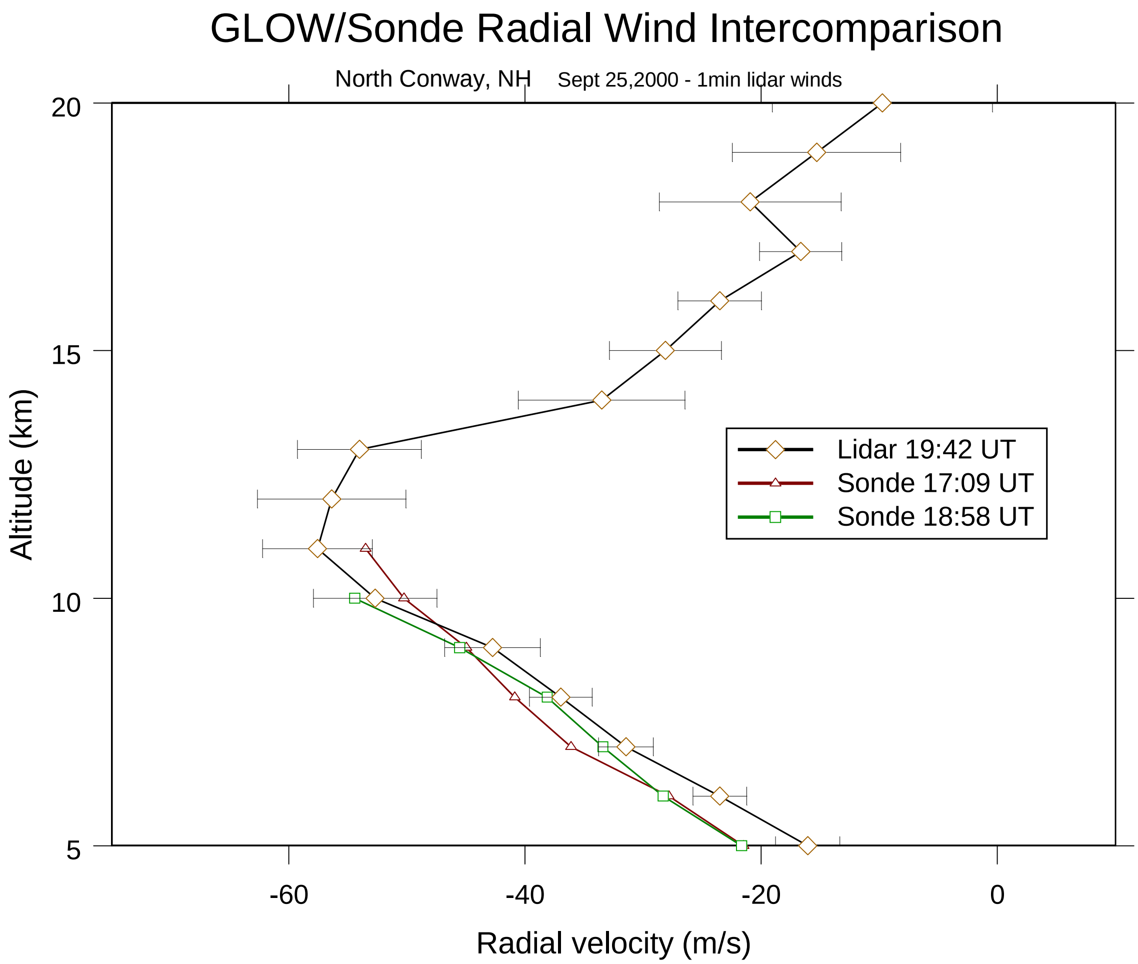

Figure 7- Mean and standard deviation of 17 one minute lidar wind profiles from the afternoon of September 25, 2000. Two rawinsonde wind profiles are also shown for comparison.

Another example from the afternoon of September 27, 2000 is shown in Figure 8. This is the mean and standard deviation of 50 lidar profiles obtained beginning at 15:38 EDT. The elevation angle was 45 degrees and the lidar was pointed N-NW at an azimuth of 45 degrees. The two sondes launched closest to the lidar sampling time are also shown for comparison. Once again the agreement is quite good through the entire altitude range up to 20 km. The error bars are substantially larger for this set of data than for the data of Figure 7 because the longer sampling interval (50 minutes vs. 17) has significantly more atmospheric variability.

5. Summary

A mobile ground based Doppler lidar using direct detection techniques is described. The lidar has been used to obtain profiles of wind speed and direction in the free troposphere and stratosphere to altitudes as high as 35 km. The system was deployed in field experiments held at the GroundWinds Observatory in the fall of 2000. Over 50 hours of radial wind data were obtained using the GLOW system during the 10 day experiment. Initial comparisons of the GLOW radial winds with the winds from rawinsondes show good agreement. The GLOW data are also being compared with the lidar profiles obtained with the GroundWinds direct detection lidar and the MiniMOPA coherent Doppler lidar as well as with the radar profiler.

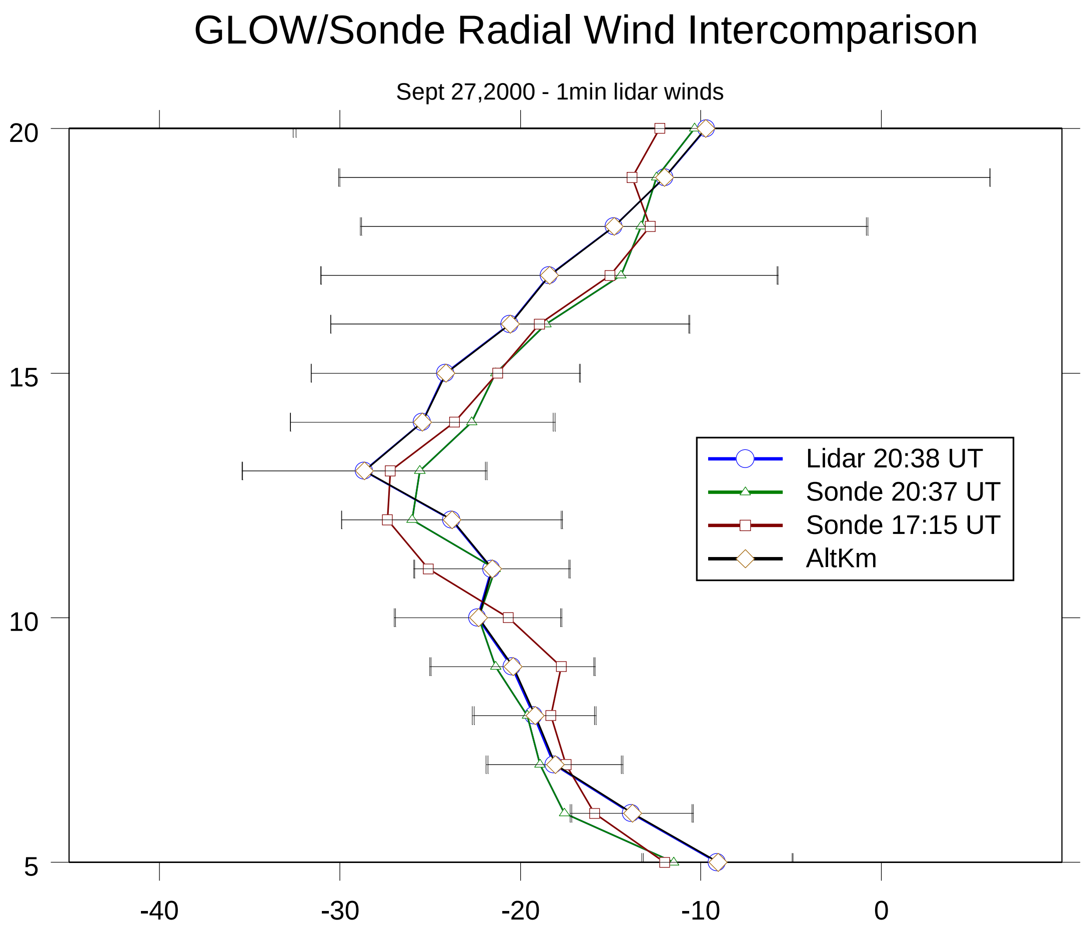

Figure 8 - Mean and standard deviation of 50 one minute lidar wind profiles from the afternoon of September 27, 2000. Two rawinsonde wind profiles are also shown for comparison.

Acknowledgements

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